

Biomechanical Tests and Finite Element Analyses of Pelvic Stability using Bilateral Single Iliac Screw with Different Channels in Lumbo-iliac Fixation

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Abstract

Background: In lumbo-iliac fixation, the iliac screw can be placed in a number of locations and directions, and multiple screws can be placed to enhance the fixation effect. At present, there is no uniform standard for the placement of single iliac screw. Biomechanical tests and finite element analyses were used to compare the effect of bilateral single iliac screw with three channels on pelvic stability in lumbo-iliac fixation, so as to provide a basis for determining the best single iliac screw channel.

Methods: Five adult embalmed cadaver pelvic specimens were selected. Unstable Tile C1 pelvic injury model (pubic symphysis separation and left sacral Denis II fracture) was established. The pubic symphysis was fixed with five-hole reconstruction plate. Lumbo-iliac fixation for the treatment of pelvic posterior ring injury: three channels of bilateral single iliac screw (channel A from PSIS to AIIIS, channel B from 1 cm medial and 1 cm caudal of PSIS to AIIIS, channel C from 2 cm below PSIS to AIIIS). At the same time, the finite element model of unstable pelvic posterior ring injury treated with lumbo-iliac fixation was established, which were used to analyze and explore the effect of bilateral single iliac screw with three channels on the biomechanical stability of the pelvis, including the stress distribution and the maximum Von Mises stress of internal fixation, vertebral body and ilium.

Results: Biomechanical tests revealed that under vertical compression load, the compressive stiffness of pelvic specimens fixed with three channels of bilateral single iliac screw was lower than that of complete pelvic specimens ($P < 0.05$). The vertical displacement fixed by channel B was smaller than that fixed by channel A and channel C; however, there was no significant difference between channel B and channel A ($P > 0.05$). The compressive stiffness fixed by channel B was better than that fixed by channel A and channel C. Under torsional load, the torsional stiffness fixed by channel B was stronger than that fixed by channel A and channel C. Finite element analyses conformed that the maximum Von Mises stress of the internal fixator fixed in channel B under the conditions of vertical, forward bending, backward extension, left bending, left rotating and right bending were significantly lower than that fixed in channel A and channel C. Under various working conditions, the maximum Von Mises stress of the internal fixture of channel B was less than that of channel A. In terms of the maximum Von Mises stress of the vertebral body and iliac, compared with the other two iliac screw channels, the overall stress distribution fixed by channel B was more reasonable.

Conclusions: Bilateral single iliac screw with three channels in lumbo-iliac fixation could effectively restore pelvic stability. The construct stiffness of the channel from 1cm medial and 1cm caudal of PSIS to AIIIS is better than that of the other two channels. This channel has the advantages of good biomechanical stability, reasonable stress distribution, small maximum Von Mises stress of internal fixation, strong fatigue resistance and not easy to break screws and rods.

Background

Sacral fractures often caused by high energy injuries such as car accidents and falls account for 17 % -30 % of pelvic fractures [1], which is easy to be accompanied by fractures of other parts, nerve injury and internal organ injury [2]. The main reason for disability and dysfunction in the late stage of patients is lumbosacral plexus injury [3]. The treatment of spinal-pelvic separation caused by complex sacral fractures is very difficult. Failure to perform effective fixation will seriously affect the stability of posterior pelvic ring and lumbosacral region. Iliolumbar fixation has become one of the reliable fixation methods [4]. Käch et al [5].1994 reported for the first time that five patients with unstable longitudinal vertical fractures of the sacrum (Denis II or III fractures) were treated with L5 pedicle screw combined with iliac screw fixation. The follow-up results were satisfactory and the internal fixation was reliable. Schildhauer et al. [6] proposed a triangular fixation technique that combined spinal-pelvis fixation system with sacroiliac screw fixation. Biomechanical studies showed that triangular fixation technique could further increase the stability between spinal and pelvis, enhance the fixation strength [7].

In lumbo-iliac fixation, the screw-rod connection system is very flexible, and the iliac screw can be placed in a number of locations and directions, and multiple screws can be placed to enhance the fixation effect. A review of the literature found that there were multiple anchoring channels during iliac screw fixation: from the posterior superior iliac spine (PSIS) to the iliac crest [8], from PSIS to the anterior inferior iliac spine (AIIS) [9], from 1cm medial and 1cm caudal of PSIS to AIIS, channel C from [10], from 2cm below PSIS to AIIS [11], and from the posterior inferior iliac spine (PIIS)to AIIS [12]. etc. At present, there is no uniform standard for the placement of iliac screw, nor has the biomechanical effect of bilateral single iliac screw with different channels on pelvic stability been explored.

According to the study of biomechanical conduction and mechanical distribution, the fixation strength of iliac screw in the lower column of iliac bone was higher than that in the upper column of iliac bone [13]. The most commonly used channel in clinic is from PSIS to AIIS. Many scholars believed that this channel can be inserted into the iliac screw with the maximum length and diameter. Biomechanical studies mostly used this channel for experimental research [13,14]. However, the clinical application of the iliac screw through this channel is prone to complications such as local skin necrosis caused by the protrusion of the internal plant, which may cause serious consequences, such as incision infection, exposure of the internal plant, etc. During the operation, part of the bone of the PSIS needs to be bitten. Harrop et al. [10] proposed a modified iliac screw fixation technique that 1cm medial and 1cm caudal of PSIS to AIIS. It was pointed out that the modified channel was more convenient and practical in clinical application than 'traditional' channel, and had fewer complications. The modified iliac screw fixation technique does not cause the usual prominence in the sacral region, and does not require lateral connector. Schwend et al [11] proposed the channel from 2cm below PSIS to AIIS. Through autopsy and biomechanics, it was confirmed that the mechanical strength of the iliac screw in this channel was more than three times that of the traditional Galveston system. Tian et al. [12] found that the channel from PIIS to AIIS was below or just on the edge of the sciatic notch in about 61.1% of Asian pelvic specimens, and there was the possibility of nerve injury. The authors pointed out that iliac screw placement in this channel were not recommended.

The aim of this study was to compare the effect of bilateral single iliac screw with three channels on pelvic stability in lumbo-iliac fixation using biomechanical tests and finite element analyses. First, a pelvis Tile C1 injury model was constructed: pubic symphysis separation and DenisⅡ fracture of the left sacrum. Second, ilio-lumbar fixation for pelvic instability injuries and bilateral single iliac screw with three channels: channel A from PSIS to AIIIS, channel B from 1cm medial and 1cm caudal of PSIS to AIIIS, channel C from 2cm below PSIS to AIIIS. Third, biomechanical tests and finite element analyses were used to analyze the biomechanical mechanism and determine the best iliac screw placement channel, so as to provide scientific basis for more reasonable and effective clinical application.

Methods

Preparation of pelvic specimens

Five adult embalmed cadaveric pelvic specimens (provided by the Department of Anatomy, Shandong First Medical University) were selected, including three male and two female, aged 42 – 58 years old, with an average of 48.3 years old. The L3 vertebral body was reserved to 10 cm of the proximal femur of both sides (Figure 1). Pelvic fracture, tumor, forced spondylitis, sacroiliac sclerosis, rheumatoid arthritis and other diseases were excluded by examination, and osteoporosis was excluded by bone density test. Specimens were wrapped in double plastic bags and stored at -20°C. The specimens were thawed at room temperature. Skin, muscle, fat and other tissues were removed. The complete pelvic bone, ligament structure and hip joint were retained. The ligament structure mainly included suprapubic ligament, pubic arch ligament, sacroiliac posterior ligament, sacroiliac anterior ligament, sacroiliac interosseous ligament, hip joint accessory ligament. The upper and lower ends of the specimens were embedded with methyl methacrylate-polymer resin to enable fixation to the mechanical testing machine.

Establishment and fixation of pelvic Tile C1 injury model

After the creep was eliminated, experimental results from biomechanics tester of complete pelvis specimens were used as control group. Then, the pubic symphysis was cut with electric saw, and the left sacral Denis II fracture was established (Figure 1). A series of surgical procedures were subsequently performed by Professor Baisheng Fu. Anatomical reduction of pelvic fracture was performed. Five-hole reconstruction plate was used to fix the separated pubic symphysis and lumbo-iliac fixation (the L4, L5 pedicle screws (6.5-mm diameter, 45-mm long), and iliac screws (7.5-mm diameter, 80-mm long), Medtronic-WeiGao Inc., WeiHai, China) was used for the treatment of unstable posterior pelvic ring injury: three channels of bilateral single iliac screw, including channel A from PSIS to AIIIS, channel B from 1cm medial and 1cm caudal of PSIS to AIIIS, channel C from 2cm below PSIS to AIIIS (Figure 2). The pedicle screws were laterally straight and parallel to the vertebral endplate. The iliac screws were entering from three channels and a 7-mm ball tip feeler was inserted into the channel to ensure its completion. Subsequently, the 7.5-mm diameter iliac screws were placed. Finally, L4-L5 pedicle screws and iliac

screws were connected by a curved rod and a cross-link was fixed between the L5 pedicle screws and iliac screws.

Biomechanical tests

The pelvic specimens were fixed on the special fixture of the American E10000 material mechanics testing machine (Provided by Institute of Orthopedics, Soochow University) (Figure 2). The L3 vertebral body was kept in a horizontal state at all times. Bilateral anterior superior iliac spine and pubic symphysis were placed on the same coronal plane in order to simulate the force on the pelvis when standing. The compression load of L3 vertebral segment was 0-500N [15] and the stress load speed was 3 mm/min through the upper loading connector. The analysis software Bluehill 2.0 provided by the mechanical testing machine automatically recorded the load-displacement curve and calculated the compressive stiffness (N/mm). Each model was tested three times and averaged. After each test cycle was completed, the pelvic specimen was carefully checked to be complete and the internal fixators did not loosen or break, the next channel test was randomly carried out. In the torsional load experiment, 6N·m torsional load was applied to the specimen through the rotational axis. The torque-torsional Angle curve was automatically recorded by WaveMatrix software and calculated the torsional stiffness (N·m /°). The same, each specimen was tested three times, and the average rotation angle was calculated. During the experiment, normal saline was sprayed regularly to keep the specimen moist.

Finite element injured models and finite element analyses

One normal adult male volunteer (48 years old, 175cm, 70Kg) was recruited. The study protocol was approved by the Ethics Committee of Shandong Provincial Hospital. The volunteer agreed with written informed consent. The radiographic data of lumbar spine, pelvis and femur were obtained by CT scan (Siemens Spiral CT, Germany, 0.625mm slice thickness), and imported into Mimics 21.0 (Materialise, Belgium) in Dicom format. And, then, these files were processed by Geomagic studio 12.0 (Geomagic, USA). Pro/Engineer 5.0 (PTC, USA) and Hypermesh 2017 (Altair, USA) were used to draw iliac screw, pedicle screw, longitudinal rod, connector, transverse connecting rod and reconstruction plate, screw, etc. The material properties and characteristics, Young's modulus, and the structure of the model ligament were set. The three-dimensional finite element model of L4-pelvic-proximal femur, pedicle screw and iliac screw were imported into Ansys 19.0 (SASI, USA) for finite element analyses (Figure 3). The finite element model included lumbar (L4 and L5), pelvis, and proximal femur. The full pelvis was composed of the left ilium, sacrum, right ilium, and symphysis pubis, and these bones consisted of the cortical bone and cancellous bone. The anterior sacroiliac, interosseous sacroiliac, posterior sacroiliac, sacrotuberous, and sacrospinous ligaments were also created to simulate normal condition. The linear elastic isotropic material properties were used, and the properties of the bones and ligaments were shown in Table 1. The same, the pelvic Tile C1 injury model (pubic symphysis separation, left sacral Denis II fracture) was established. Simulate 5-hole reconstruction plate fixation of the pubic symphysis and lumbo-iliac fixation

for the treatment of posterior pelvic ring surgery. Finite element analyses were used to explore the biomechanical characteristics of bilateral single iliac screw, divided into three channels: channel A from PSIS to AIIIS, channel B from 1cm medial and 1cm caudal of PSIS to AIIIS, channel C from 2cm below PSIS to AIIIS. The number of elements for implants was 1,713,729 for channel A, 1,715,997 for channel B, and 1,713,492 for channel C, respectively. The number of nodes for implants was 2,794,487 for channel A, 2,798,784 for channel B, and 2,795,149 for channel C, respectively. The standing state of the human body was simulated and the boundary conditions were set at the bilateral femoral ends. The 500 N vertical downward load was applied on the upper surface of L4 vertebral body, and the torque in different directions of 10 N·m was applied to simulate the working conditions of flexion, extension, lateral bending and rotation. The stress nephogram, displacement nephogram and deformation nephogram of the internal fixation, vertebral body and iliac bone were obtained by finite element software. The maximum von Mises stress of internal fixation and the maximum von Mises stress of vertebral body and ilium in different channels were compared.

Statistical methods

The maximal compressive displacement and torsional angle between the peak and trough points of curves were obtained. The compressive and torsional stiffness of fixation construct were calculated by the following formulas:

Compressive stiffness = 500 (N) / maximum compressive displacement (mm)

Torsional stiffness = 6 (N·m) / maximum torsional angle (°)

SPSS software (version 20.0 Chicago, IL, USA) was used for statistical description and analysis of the experimental results. The measurement data were expressed as mean \pm standard deviation (SD). The experimental data were tested to meet the normal distribution and the homogeneity of variance. One-way analysis of variance was used for comparison between groups. LSD method was used for pairwise comparison. The difference was statistically significant when $P < 0.05$.

Results

Biomechanical tests

After the unstable pelvic ring injury model was fixed with three channels of bilateral single iliac screw, the overall displacement of pelvic specimens under 500 N vertical load was greater than that of complete pelvic specimens (1.852 ± 0.104 mm), and the difference was statistically significant ($P < 0.05$) (Table 2). The vertical displacement fixed by channel B (2.054 ± 0.248 mm) was smaller than that fixed by channel A and channel C (2.153 ± 0.175 mm and 2.370 ± 0.167 mm, respectively), and the difference in the vertical displacement fixed by channel B and channel A was not statistically significant ($P > 0.05$). The compressive stiffness of bilateral single iliac screw in three channels was significantly lower than that of

complete pelvic specimens (270.7 ± 15.38 N/mm), and the difference was statistically significant ($P < 0.05$) (Table 2). The compressive stiffness of channel B (246.15 ± 27.85 N/mm) was greater than that of channel A and channel C (233.43 ± 18.5 N/mm and 211.79 ± 14.58 N/mm, respectively), but there was no significant difference between channel B and channel A ($P > 0.05$). The compressive stiffness of channel A and channel C were significantly different from that of complete pelvic specimens ($P < 0.05$).

The overall torsional angle of pelvic specimens fixed with three channels of bilateral single iliac screw under 6 N·m torsional load was greater than that of complete pelvic specimens ($2.419 \pm 0.176^\circ$), and the difference was statistically significant ($P < 0.05$) (Table 3). The torsional angles of channel A and channel C ($2.973 \pm 0.274^\circ$, $3.411 \pm 0.197^\circ$, respectively) were significantly different from those of complete pelvic specimens ($P < 0.05$). The torsion angle of pelvic specimens fixed by channel B ($2.708 \pm 0.280^\circ$) was less than that of pelvic specimens fixed by channel A and channel C, and the difference was statistically significant ($P < 0.05$). The torsional stiffness of bilateral single iliac with three channels was lower than that of the complete pelvic specimen (2.491 ± 0.184 N·m/°), and the difference was statistically significant ($P < 0.05$). The torsional stiffness of channel C (1.764 ± 0.101 N·m/°) was smaller than that of channel A and channel B ($P < 0.05$) (Table 3). There was no significant difference in torsional stiffness between channel A (2.032 ± 0.187 N·m/°) and channel B (2.234 ± 0.223 N·m/°) ($P > 0.05$).

Finite element analyses

In terms of the overall stress distribution nephogram, the maximum Von Mises stress showed on the internal fixator. There was a large stress concentration in the iliac screw, connector and longitudinal rod, and the tail of the iliac screw and the surrounding of the connector were more obvious (Figure 3). The maximum Von Mises stress of the internal fixator fixed in channel B under the working conditions of vertical, forward bending, backward extension, left bending, left rotating and right bending (213.98MPa, 338.96MPa, 100.63MPa, 297.06MPa, 200.95MPa, 284.75MPa, respectively) were significantly lower than the maximum Von Mises stress of internal fixators fixed in channel A and channel C (Table 4, Figure 4). The same, under various working conditions, the maximum Von Mises stress of internal fixator of channel B was less than that of channel A (Table 4, Figure 4). Under the vertical condition, the maximum Von Mises stress of internal fixator in channel B was 71.4% of that in channel A. Under the left rotation condition, the maximum Von Mises stress of the fixator in channel B was only 65.9% of that in channel A. It showed that the maximum Von Mises stress of the fixator in channel B was the smallest, the fatigue resistance was strong, and the less prone to broken screws.

In various working conditions, except extension, the maximum Von Mises stress of the vertebral body was: channel A < channel B < channel C. In terms of the maximum Von Mises stress of iliac, under the conditions of upright, forward bending, left bending and right rotation, channel A > channel B. The results showed that the overall stress distribution of the channel B was more reasonable.

Discussion

Spinal-pelvic fixation can treat many diseases of trauma surgery and spinal surgery [16], aiming to rebuild the stability of the spine and pelvis, such as traumatic spinal pelvic separation ('H or U' shaped fractures of the sacrum, etc.), complex sacral comminution fractures, sacrum fracture complicated with nerve injury, spinal protrusion deformity, the sacrum tumor, tuberculations of the lumbar and sacrum, severe lumbar spondylolisthesis, and scoliosis combined pelvic tilt. Lumbo-iliac fixation for the treatment of U-type sacral fractures has been reported in many literatures, and this treatment can provide multi-planar stability [17,18]. Fujibayashi et al. [19] used iliolumbar fixation for palliative treatment of sacral destructive tumors and achieved satisfactory clinical efficacy. The authors pointed out that this fixation method could increase the stability of lumbosacral region. Ebata et al. [20] applied spinal-pelvic fixation system in adult spinal deformity correction and achieved satisfactory results. Futamura et al. [21], Koshimune et al. [22], Okuda et al. [23] used small incision minimally invasive lumbo-iliac fixation to reduce the risk of skin and soft tissue injury and infection, and improve the healing rate of fracture. Song et al [24] compared the biomechanical characteristics between bilateral and unilateral lumbo-iliac fixation in unilateral comminuted sacral fractures by finite element analysis and the results revealed that the stability of unilateral lumbo-iliac fixation is insufficient to reconstruct the posterior pelvic ring. Furthermore, the unilateral fixation may lead to imbalance of lumbar vertebra and pelvis. On the contrary, the bilateral lumbo-iliac fixation can provide satisfied stability and lumbar balance. So bilateral lumbo-iliac fixation was selected in this study and the finite element results showed that stress distribution nephogram of L4, L5, the acetabulum and femur were balance, and because the fracture line is on the sacrum, the stress distribution in the sacrum was uneven. The results were similar to those of song's authors.

The iliac screw technique in spine-pelvis fixation has been widely used, and reliable lumbar and pelvis stability has been obtained clinically. The iliac screw is developed by Harrington, Luque, and Galveston technology, which largely overcomes the previous problems of insufficient biomechanical strength, screw loosening, fracture, local pseudarthrosis formation, and on this basis, it provides a stronger and stable fixation device and a more flexible and convenient connection device, which is easy to operate and has widely clinical application.

There are many options for iliac screw placement sites and channels. The technique of iliac screw is theoretically to fix the length behind the iliac bone to the maximum extent so that the strength of the screw fixation is the strongest, and the prominence of the internal fixation is avoided. At present, it is not clear which channel of iliac screw is best for fixation. In addition, Miller et al. [25] studied the anatomy of cadaver pelvic specimens, believed that when the length of the inserted iliac screw reached 100mm and was located in the channel from PSIS to AIIIS, there was a 25% probability of penetrating the acetabulum and entering the joint. Therefore, the scholar suggested that the length of iliac screw should be less than 90mm. Moshirfar et al. [26] made a retrospective analysis of the literature on clinical application of iliac screws, and believed that the length of iliac screws should be greater than 80mm and the diameter should be 7.5mm, which was of high effectiveness and good safety. Therefore, the use of iliac screw lengths ranging from 70mm (above the level of the greater sciatic notch) to 90mm has become a clinical

consensus. In this study, the iliac screw was 80mm in length and 7.5mm in diameter and all the ilium screws were within the ilium channel and did not exceed the total length or diameter of the channel.

The biomechanical differences of three channels of bilateral single iliac screw in inferior iliac column were studied. Compared with previous biomechanical studies, such as sacroiliac screws, posterior ring tension band plates and sacrum rods. etc, the results showed that three channels of bilateral single iliac screw in lumbo-iliac fixation could effectively restore the stability of the reconstructed pelvis. The compressive stiffness of channel A was 86.2 % of the complete pelvis, the compressive stiffness of channel B was 90.9 % of the complete pelvis, and the compressive stiffness of channel C was 78.2 % of the complete pelvis. According to the compressive stiffness and torsional stiffness of the pelvic specimens, there was no significant difference between channel B and channel A, but the results of channel B fixation was greater than that of channel A fixation. The reason we consider is that the fixed distance between channel A and channel B is very close, and both of them are close to the normal mechanical conduction path. The fixed strength of channel B is better than that of channel A. The study also showed that the construct stiffness of channel C was worst. The fixed position of channel C is lower. When the pelvic specimen is in a standing position, the normal force conduction path is higher than the fixed position of channel C, resulting in large vertical displacement of the pelvis and weak fixation strength. When the human body is sitting, the normal mechanical conduction path moves down, making the fixation of channel C close to normal and high fixation strength. However, we do not perform a sitting-time biomechanical test, and this interpretation requires further confirmation.

Finite element analysis has been widely used in the field of medical research, and it mainly is based on the digital model to evaluate the immediate stability of body internal fixation stability (overall stability and local stability), the body's stress distribution nephogram and rigid structure, the maximum Von Mises stress and stress distribution nephogram of internal fixation and the stress distribution of the adjacent structures [27]. In this study, the results showed that the maximum Von Mises stress of model showed on the internal fixation was the largest, followed by the vertebral body, and the maximum Von Mises stress of the iliac bone was the smallest.

The stress of the internal fixation device should not be excessively concentrated at a certain point, so as to avoid the fracture of the screw rod system due to excessive stress concentration [28]. In addition, a standard reflecting the safety performance of the internal fixation device is the maximum stress it bears. After applying the load, the greater the maximum stress of the internal fixation is, the greater the possibility of complications such as broken screws, broken rods and the failure of the fixation device is. In this study, the results showed that the iliac screw, connector and longitudinal rod had high stress concentration. The stress nephogram of the internal fixation showed that the maximum Von Mises stress was mainly concentrated on the tail of the iliac screw and around the connector, which was the position where the screw-rod system was prone to fracture in spine-pelvic fixation. And, the maximum Von Mises stress of internal fixation in channel B under all the conditions were smaller than those in channel A. The maximum stress value of internal fixation in C channel was the largest in three channels. The results

showed that the stress distribution of channel B was scattered, the maximum Von Mises stress of the internal fixation was small, and the fatigue resistance was strong.

An important criterion for the evaluation of surgical quality is the stress on the intervertebral disc after operation. The greater the maximum stress on the intervertebral disc is, the more likely it will lead to degenerative changes of the intervertebral disc and symptoms such as low back pain [29]. In all conditions except extension, the maximum Von Mises stress of vertebral body: channel A fixation was less than channel B fixation, and channel B fixation was less than channel C fixation. In terms of the maximum Von Mises stress of iliac bone: under the conditions of upright, flexion, left bending and right rotation, the maximum stress of the iliac bone fixed by channel A was greater than that of the iliac bone fixed by channel B. It can be seen that the overall stress distribution of the channel B fixation model was more reasonable.

There were some defects in this study: first. Use specimens for biomechanics: as corpse specimens were relatively precious, the number of specimens was small, and there were differences among specimens. Multiple fixation devices have been tested on the same specimen, but the influence between the fixation devices before and after the fixation could not be eliminated, and errors could not be avoided. Second, the establishment of finite element model involved many aspects, and there was a certain gap between the constructed pelvic model and the real pelvis. The assignment of bone material properties is a difficult problem to solve, and at present, the characteristics of bone heterogeneity and anisotropy cannot be well simulated. At the same time, this study did not simulate the muscle structure around the human pelvis, which limited the freedom of the femoral tip in six directions and could not simulate the normal physiological activity of the human body. Third, the biomechanical experiment is only the verification of the biomechanical properties of a certain fixation method, which can only be used as a reference for clinical application. We should consider the short-term and long-term clinical effects.

Conclusions

Biomechanical tests of pelvic specimens treated with lumbo-iliac fixation for unstable posterior pelvic ring injury showed that bilateral single iliac screw with three channels could effectively restore the stability of the reconstructed pelvis. The compressive stiffness and torsional stiffness of the channel B fixation were better than those of the channel A fixation. The compressive stiffness and torsional stiffness of the channel C fixation were worst. In terms of finite element analyses, channel B fixation has good biomechanical stability, the overall stress distribution is more reasonable, the maximum stress value of internal fixation is small, with strong fatigue resistance, and it is not easy to break nails. It is suggested that in the clinical application of lumbo-iliac fixation, the optimal iliac screw channel is 1cm medial and 1cm caudal of the posterior superior iliac spine to the anterior inferior iliac spine.

Abbreviations

PSIS: Posterior superior iliac spine

AIIS: Anterior inferior iliac spine

PIIS: Posterior inferior iliac spine

Declarations

Ethics approval and consent to participate

The study protocol was approved by the Ethics Committee of Shandong Provincial Hospital. Written informed consent was obtained from the volunteer included in this study. Declared that all methods were carried out in accordance with relevant guidelines and regulations.

Consent for publication

Not applicable

Availability of data and materials

The datasets used and analyzed during the present study are available from the author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

YS YF BF performed the experiments and wrote this manuscript. YS FL HM WZ BF collected and analyzed the data. QL DZ BF revised and finalized the study. All authors read and approved the final manuscript.

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References

1. Herman A, Keener E, Dubose C, et al. Zone 2 sacral fractures managed with partially-threaded screws result in low risk of neurologic injury. *Injury*. 2016;47(7):1569–1573.
2. Bydon M, De la Garza-Ramos, R, Macki M, et al. Incidence of sacral fractures and in-hospital postoperative complications in the United States: an analysis of 2002-2011 data. *Spine*,2014,39(18): e1103-1109.
3. Denis F, Davis S, Comfort T. Sacral fractures: an important problem. Retrospective analysis of 236 cases. *Clin Orthop Relat Res*. 1988;227(227):67.
4. Quacinella MA, Morrissey PB, Parry JA, Mauffrey C. Spinopelvic Dissociation: Assessment, Reduction Strategies, and Fixation Techniques. *J Am Acad Orthop Surg*. 2020;28(24): e1086-e1096.
5. Käch K, Trentz O. Distraction spondylodesis of the sacrum in "vertical shear lesions" of the pelvis. *Der Unfallchirurg*, 1994, 97(1):28–38.
6. Schildhauer T A, Ledoux W R, Chapman J R, et al. Triangular osteosynthesis and iliosacral screw fixation for unstable sacral fractures: a cadaveric and biomechanical evaluation under cyclic loads. *J Orthop Trauma*, 2003, 17(1): 22–31.
7. Berber O, Amis A A, Day A C. Biomechanical testing of a concept of posterior pelvic Reconstruction in rotationally and vertically unstable fractures. *Journal of Bone and Joint Surgery-British Volume*, 2011, 93B(2): 237–244.
8. Schildhauer TA, McCulloch P, Chapman JR, et al. Anatomic and lumbopelvic fixation. *J Spinal Disord Tech*,2002,15(3):199–205.
9. Bourghli A, Boissiere L, Obeid I. Dual iliac screws in spinopelvic fixation: a systematic review. *Eur Spine J*. 2019;28(9):2053–2059.
10. Harrop JS, Jeyamohan SB, Sharan A, et al. Iliac bolt fixation: an anatomic approach[J]. *Journal of spinal disorders & techniques*,2009,22(8):541–544.
11. Schwend RM, Sluyters R, Najdzionek J. The pylon concept of pelvic anchorage for spinal instrumentation in the human cadaver. *Spine*,2003,28(6):542–547.
12. Tian X, Li J, Sheng W, et al. Morphometry of iliac anchorage for transiliac screws: a cadaver and CT study of the Eastern population. *Surg Radiol Anat*. 2010;32(5):455–462.
13. Yu BS, Zhuang XM, Zheng ZM, Li ZM, Wang TP, Lu WW. Biomechanical advantages of dual over single iliac screws in lumbo-iliac fixation construct. *Eur Spine J*. 2010;19(7):1121–1128.
14. Zheng Z, Yu B, Chen H, et al. Effect of iliac screw insertion depth on the stability and strength of lumbo - iliac fixation constructs: An anatomical and biomechanical study. *Spine*, 2009, 34 (16): 565–572.

15. Wu T, Ren X, Cui Y, et al. Biomechanical study of three kinds of internal fixation for the treatment of sacroiliac joint disruption using biomechanical test and finite element analysis. *J Orthop Surg Res.* 2018;13(1):152.
16. Esmende SM, Shah KN, Daniels AH. Spinopelvic Fixation. *J Am Acad Orthop Surg.* 2018;26(11):396–401.
17. Gribnau A J, van Hensbroek P B, Haverlag R, et al. U-shaped sacral fractures: surgical treatment and quality of life. *Injury*, 2009, 40(10): 1040–1048.
18. Complications associated with surgical stabilization of high-grade sacral fracture dislocations with spino-pelvic instability.
19. Fujibayashi S, Neo M, Nakamura T. Palliative dual iliac screw fixation for lumbosacral metastasis. Technical note. *J Neurosurg Spine.* 2007;7(1):99–102.
20. Ebata S, Ohba T, Oba H, Haro H. Bilateral dual iliac screws in spinal deformity correction surgery. *J Orthop Surg Res.* 2018;13(1):260. Published 2018 Oct 19.
21. Futamura K, Baba T, Mogami A, Kanda A, Obayashi O, Iwase H, et al. "within ring"-based sacroiliac rod fixation may overcome the weakness of spinopelvic fixation for unstable pelvic ring injuries: technical notes and clinical outcomes. *Int Orthop.* 2018;42:1405–11.
22. Koshimune K, Ito Y, Sugimoto Y, Kikuchi T, Morita T, Mizuno S, et al. Minimally invasive spinopelvic fixation for unstable bilateral sacral fractures. *Clin Spine Surg.* 2016;29:124–7.
23. Okuda A, Maegawa N, Matsumori H, et al. Minimally invasive spinopelvic "crab-shaped fixation" for unstable pelvic ring fractures: technical note and 16 case series. *J Orthop Surg Res.* 2019;14(1):51. Published 2019 Feb 15.
24. Song W, Zhou D, He Y. The biomechanical advantages of bilateral lumbo-iliac fixation in unilateral comminuted sacral fractures without sacroiliac screw safe channel: A finite element analysis. *Medicine (Baltimore).* 2016;95(40): e5026.
25. Miller F, Moseley C, Koreska J. Pelvic anatomy relative to lumbosacral instrumentation. *J Spinal Disord.* 1990;3(2):169–173.
26. Moshirfar A, Rand FF, Sponseller PD, et al. Pelvic fixation in spine surgery. Historical overview, indications, biomechanical relevance, and current techniques. *J Bone Joint Surg Am.* 2005;87 Suppl 2:89–106.
27. Hao Z, Wan C, Gao X, Ji T. The effect of boundary condition on the biomechanics of a human pelvic joint under an axial compressive load: a three-dimensional finite element model. *J Biomech Eng.* 2011;133(10):101006.
28. Zhang L, Peng Y, Du C, Tang P. Biomechanical study of four kinds of percutaneous screw fixation in two types of unilateral sacroiliac joint dislocation: a finite element analysis. *Injury.* 2014;45(12):2055–2059.
29. Diwan A D, Parvataneni H K, Khan S N, et al. Current concepts in intervertebral disk restoration. *Orthopedic Clinics*, 2000, 31(3):453–464.

Tables

Table 1			
The properties of Material used in finite element model			
Material	Youngs modulus (MPa)	Poissons ratio ν	K(N/mm)
Cortical bone (vertebral body)	12000	0.3	
Cancellus bone (vertebral body)	345	0.2	
Posterior element (vertebral body)	3500	0.3	
Cortical bone (ilium)	17000	0.3	
Cancellus bone (ilium)	132	0.2	
Cortical bone (sacrum)	6140	0.3	
Cancellus bone (sacrum)	1400	0.3	
Symphysis pubis	5	0.45	
Articular cartilage	100	0.3	
Plates (Titanium alloy)	110000	0.3	
Screws (Titanium alloy)	110000	0.3	
Sacroiliac posterior long ligament			1000
Sacroiliac posterior short ligament			400
Sacroiliac anterior ligament			700
Sacrotuberous ligament			1500
Sacrospinous ligament			1400

Table 2**Vertical displacement and axial stiffness of pelvic specimens under 500N [mean \pm SD]**

	Vertical displacement of pelvic specimens [mm]	axial stiffness [N/mm]
Control Group	1.852 \pm 0.104	270.7 \pm 15.38
Channel A	2.153 \pm 0.175	233.43 \pm 18.5
Channel B	2.054 \pm 0.248	246.15 \pm 27.85
Channel C	2.370 \pm 0.167	211.79 \pm 14.58
<p>Vertical displacement, <i>P Value</i>: □ Control Group and A □ B □ C <i>P</i>=0.003 Control Group and A <i>P</i>=0.011; Control Group and B <i>P</i>=0.132; Control Group and C <i>P</i> □ 0.01; □ A □ B and C <i>P</i>=0.073 A and B <i>P</i>=0.48; A and C <i>P</i>=0.079; B and C <i>P</i>=0.045</p>		
<p>axial stiffness, <i>P Value</i>: □ Control Group and A □ B □ C <i>P</i>=0.002 Control Group and A <i>P</i>=0.009; Control Group and B <i>P</i>=0.123; Control Group and C <i>P</i> □ 0.01; □ A □ B and C <i>P</i>=0.068 A and B <i>P</i>=0.42; A and C <i>P</i>=0.074; B and C <i>P</i>=0.04</p>		

Table 3**Torsional angle and torsional stiffness of pelvic specimens under torsional load of 6N·m [mean \pm SD]**

	Torsional angle of pelvic specimens [°]	Torsional stiffness [N·m/°]
Control Group	2.419 \pm 0.176	2.491 \pm 0.184
Channel A	2.973 \pm 0.274	2.032 \pm 0.187
Channel B	2.708 \pm 0.280	2.234 \pm 0.223
Channel C	3.411 \pm 0.197	1.764 \pm 0.101
<p>The torsional angle, <i>P Value</i>: □ Control Group and A □ B □ C <i>P</i> □ 0.01 Control Group and A <i>P</i>=0.005; Control Group and B <i>P</i>=0.086; Control Group and C <i>P</i> □ 0.001 □ A □ B and C <i>P</i>=0.003 A and B <i>P</i>=0.169; A and C <i>P</i>=0.019; B and C <i>P</i>=0.001</p>		
<p>The torsional stiffness, <i>P Value</i>: □ Control Group and A □ B □ C <i>P</i> □ 0.01 Control Group and A <i>P</i>=0.004; Control Group and B <i>P</i>=0.081; Control Group and C <i>P</i> □ 0.001 □ A □ B and C <i>P</i>=0.004 A and B <i>P</i>=0.159; A and C <i>P</i>=0.022; B and C <i>P</i>=0.003</p>		

Table 4			
Maximum Von Mises stress of internal fixation with three channels [MPa]			
	Channel A	Channel B	Channel C
Vertical	299.4	213.98	302.01
Forward bending	496.16	338.96	408.96
Backward extension	103.05	100.63	195.73
Left bending	390.56	297.06	335.09
Right bending	349.19	284.75	528.56
Left rotating	304.91	200.95	354.27
Right rotating	377.97	331.35	298.72

Figures



Figure 1

An unstable Tile C1 type injury of pelvis specimen.

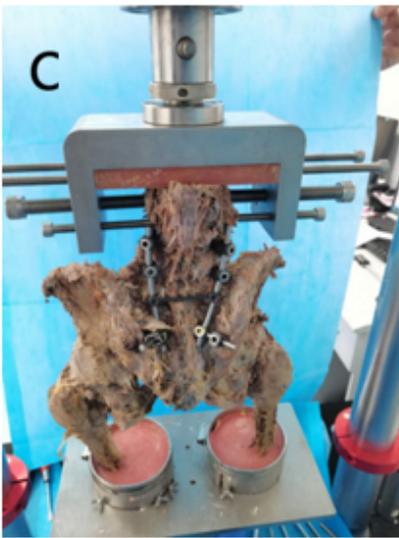
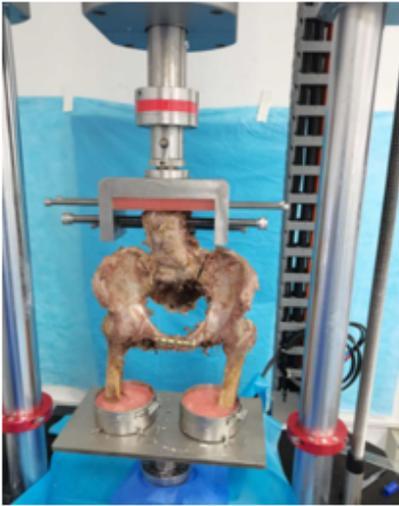


Figure 2

Biomechanical tests of bilateral single iliac screw with three channels in iliolumbar fixation: frontal view of pelvic injury model and biomechanical testing machine; a. The iliac bone screw was fixed from PSIS to AIIS; b. The iliac bone screw was fixed from 1cm medial and 1cm caudal of PSIS to AIIS; c. The iliac bone screw was fixed from 2cm below PSIS to AIIS.

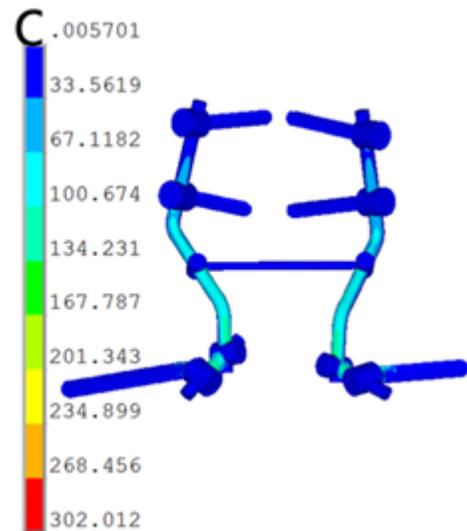
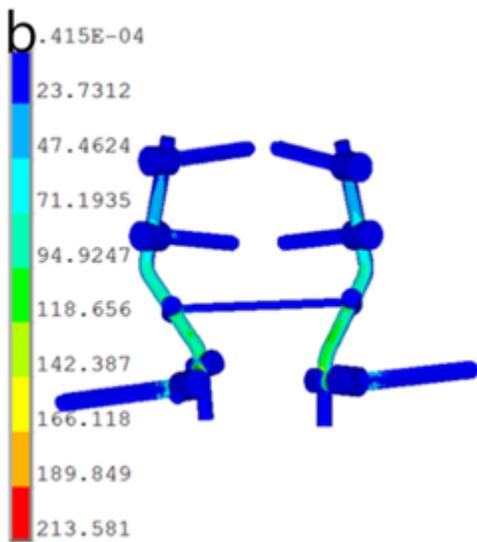
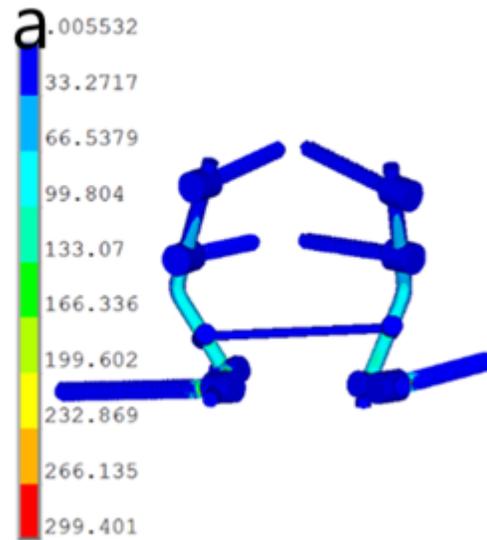
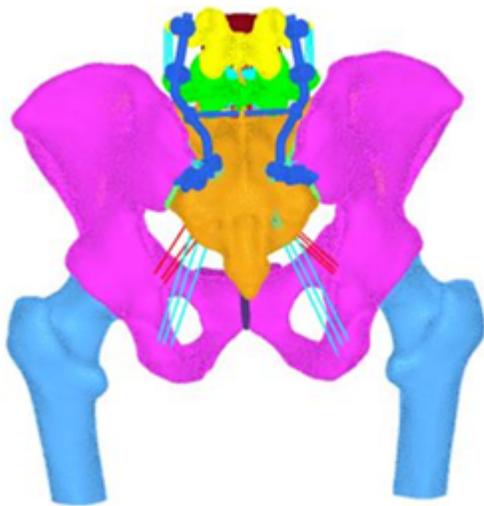


Figure 3

To establish finite analysis model of lumbo-iliac fixation: under the vertical working condition; a. stress distribution nephogram of internal fixators in channel A; b. stress distribution nephogram of internal fixators in channel B; c. stress distribution nephogram of internal fixators in channel C.

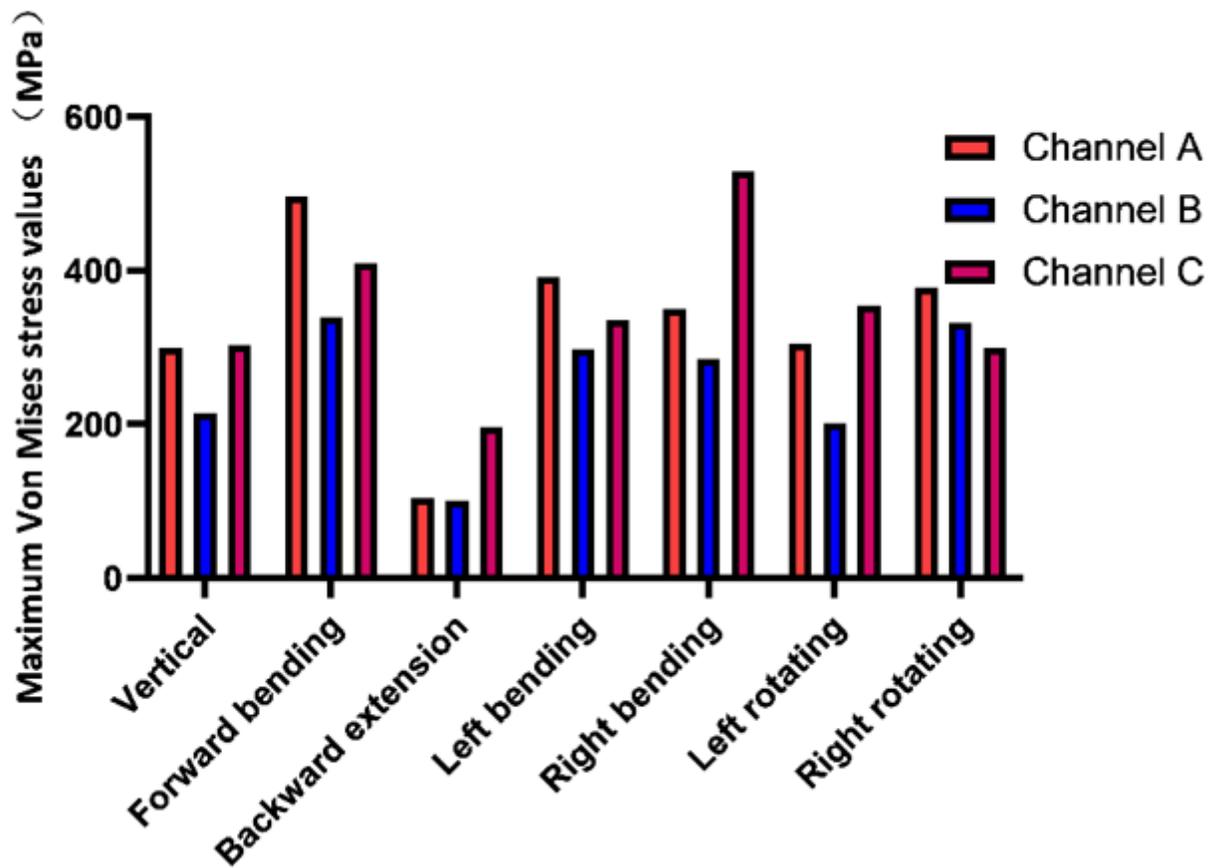


Figure 4

Maximum Von Mises stress of internal fixation with three channels